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Statistical Analysis of Relationships Between the Flow Regime and Riverine Ecosystems in the Umba River, Kenya

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Abstract

The Umba River basin is a transboundary river catchment shared between Kenya and Tanzania. It is endowed with unique and endemic plant and animal species in the coastal area. The river flow plays important role in maintaining the estuary that provides essential functions and services to the communities living in the area. To protect the freshwater biodiversity and to maintain the essential goods and services provided by the river, the components of the natural flow regime need to be investigated. The statistical analyses of relationships between the flow regime and the riverine ecosystems were evaluated using Ecosystem Functions Model (EFM). A natural flow regime composed of daily time series of water levels and discharges was analysed. Based on the flow regime and eco-hydro relationships, several statistical and seasonal results were computed for five ecosystem groups: aquatic animals, mangrove plants, riparian vegetation, macro invertebrates, and floodplain wetlands. The seasonal results presented the performance of the ecosystem groups in each water year of the flow period and the statistical results were computed as stages, flows, and percent exceedance for each relationship. The findings of this study can be considered as baseline information for comparing and identifying effective water resources development projects in the river.

Keywords: Estuary, flow regime, HEC-EFM, riverine ecosystems, Umba River

1. Introduction

The conservation and sustainable use of biodiversity is crucial for the survival of humans and protecting the environment. Thus, the maintenance of natural biodiversity is the key to the health of ecosystems and to their sustainable utilisation. Fresh water maintains riverine and estuarine biodiversity which simultaneously serve multiple aspects of human well-being and provide a wealth of goods and services for societies (Forslund et al. 2009). To sustain these benefits and maintain freshwater biodiversity, the freshwater flows must be better managed (Richter et al. 2003).

Flow regimes play major roles in regulating the biotic structures, compositions, and functions of aquatic, riparian, and wetland ecosystems (Richter et al. 1996). Maintaining natural hydrologic variability determines the structure and function of riverine ecosystem which is essential for conserving native riverine biota and integrating the river ecosystems (King, Tharme, and Villiers 2008; Wakitolie 2013). This helps to maintain the health of the riverine, wetland, estuarine, floodplain ecosystems and the services and functions that they provide. The hydrologic components of a natural flow regime control many of the physical, chemical, and biological processes that sustain biological diversity and ecosystem services of rivers (Bunn and Arthington 2002; Carlisle et al. 2010). On the other hand, alterations of a river from its natural conditions modify habitat attributes and impair ecosystems (Speed et al. 2013; Wang, Wang, and Wu 2015).

Seasonally, stream ecosystems undergo major changes in biota and ecological processes (Lake 2005). The natural flow variability creates and maintains hydrological and ecological connectivity between the river channel, floodplain, wetland, and estuary. The ecosystem functions and biodiversity have evolved under this natural river flow variations and rivers with highly altered flows lose their ability to support the natural processes of maintaining healthy diverse ecosystems. This in turn diminishes the services provided by the healthy river ecosystems. It is therefore essential to understand the linkages between the seasonal freshwater inflows and the riverine ecosystems (FIU-GLOWS 2016).

The alteration of flow regimes is the most serious and continuing threat to the biodiversity and ecosystem functions of rivers and their associated floodplain wetlands (Nilsson and Berggren 2000; Bunn and Arthington 2002). Flow alteration involves modification of the natural flow regime components in magnitude, duration, timing, frequency, and rate of change (Poff and Zimmerman 2010). In rivers where the flow pattern has been altered by man, all of these components are likely to change from their natural conditions (King, Tharme, and Villiers 2008).

When natural flow regimes are altered by dams, diversions, and land-use practices, the existing environmental conditions and habitat to which native species have been adapted are disturbed. Additionally, the geomorphic processes on which many species rely for habitat creation and maintenance are modified, thereby disrupting the life stages of native aquatic and floodplain species (Bunn and Arthington 2002). Reduced connectivity between habitats is also another consequence of flow regime alteration (Julian et al. 2015). When natural variability in river flows is altered too much, significant changes in the physical, chemical, and biological conditions and functions of the river ecosystems occur. When changes to natural flow regimes are excessive, the impacts are high to both the biodiversity and societies (Richter et al. 2003).

Provision of sufficient freshwater flow ensures the functioning of riverine ecosystems and maintains the goods and services sustained by the water-dependent ecological processes (Rivaes et al. 2017). The river environment and the functional integrity of the riverine ecosystem can be maintained if the features of the natural flow regime can be identified and adequately incorporated into a modified flow regime (King, Tharme, and Villiers 2008; Wakitolie 2013). To protect the freshwater biodiversity and to maintain the essential goods and services provided by rivers, therefore, the components of the natural flow regime need to be investigated (Arthington et al. 2006). These require understanding the key components of the flow regime and their roles in maintaining the health of the ecosystems.

The Umba River basin is a transboundary river catchment shared between Kenya and Tanzania. It is endowed with unique and endemic plant and animal species in the coastal area (Mitto et al. 2013). The estuary supports abundant and diverse ecosystems, the majority of which are located at the end of the river which makes them susceptible to the effects of flow regime changes. The river flow plays important role in maintaining the estuary that provides essential functions and services to the communities living in the area (VAJIKI PFMP 2017). Freshwater input from the river is a major factor controlling the estuarine production which is critical for the biodiversity of the coastal and marine ecosystems, and the livelihoods they support. Due to the threats from the growing human pressures and climate change-related effects, however, there is growing concern on the alteration of the river flow that can significantly affect the functioning of the estuary (Mitto et al. 2013).

Moreover, the lower catchment has a great potential for large-scale irrigation and currently there are plans to construct two dams on the catchment to meet the water demands for irrigation and water supply (Lerise 2005). After development of the dams, the amount of water withdrawn from the river is likely to increase, leading to a decrease in the amount of freshwater delivered to the estuary. This will cause negative impacts on the ecosystems in the lower reach of the river. Therefore, analyses of the natural flow regime need to be done to preserve the riverine ecosystems and sustain their services.

The integration of hydrologic and ecological data is essential to assess the flow needs in the Umba River. Assessment of the river flow requires understanding the key components of the flow regime and their roles in maintaining the health of the ecosystems (Arthington et al. 2006; Poff et al. 2010; Poff and Zimmerman 2010). The historical natural flows entering the estuary need to be investigated to extract ecologically meaningful flow components that capture the natural flow variability. Analysis of the relationships between the historical flow regime and the ecosystems of the river helps to identify important flow dynamics that satisfy the timing of species life stages and requisite conditions for their success. The overall objective of this study is, therefore, to perform statistical analyses of relationships between the flow regime and the riverine ecosystems of the Umba River using Ecosystem Functions Model (EFM).

2. Materials and Methods

2.1 Description of the Study Area

The study area is located in the lower 45 km reach of the Umba River (Figure 1). The Umba River Basin is a transboundary river catchment shared between Kenya and Tanzania. It covers a total area of 8,070 km^2 of which about 5510 km^2 is in Tanzania and the remaining 2,560 km^2 lies in Kenya. Originating from the Usambara Mountains in Tanzania, the river's main catchment lies in the northeast Tanzania. The river drains southeast and crosses the Tanzania-Kenya border and enters the Indian Ocean through a huge mangrove system at Vanga Town of Kenya. The flow of the river is characterized by high seasonal variability, attributed to land-use changes and climate variability within its upper catchment areas (IUCN Eastern Africa Programme 2003; Lerise 2005).

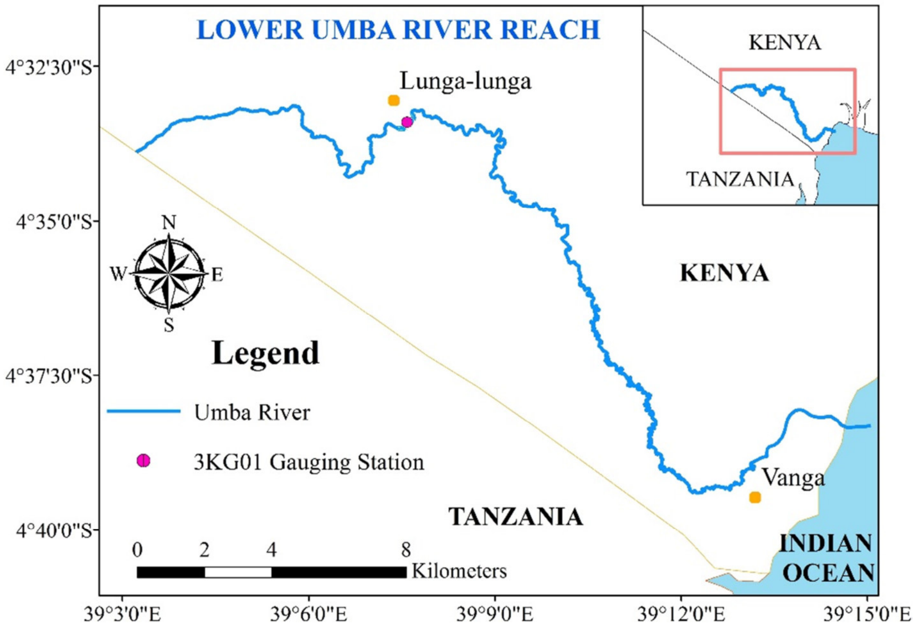

Figure 1. Location of the Study Area

The average annual temperature in the study area is 26 °C and it receives an annual average rainfall of 900 mm. High mean temperatures are experienced in the months of November and April while the coolest period is between June and August. The basin is mainly characterized by tropical climate dominated by the large scale pressure systems of the Western Indian Ocean resulting two distinct monsoon periods. It experiences a bi-modal rainfall pattern, with the short rainy season occurring between November and January and the long rainy season occurring between March and May (CWSB 2013; VAJIKI PFMP 2017; Wang'ondu et al. 2010).

The land cover of the area is dominated by mangrove forest, mosaic vegetation, grassland, and cropland and the main land uses include cattle grazing and irrigation (IUCN Eastern Africa Programme 2003). The water in the Umba River is a critical resource to the livelihoods of the communities living around it for its use in domestic water supply, irrigation, the environment, and other uses (Lerise 2005). The livelihoods of the people living around the estuary are tightly linked to the environmental services that the estuary provides. Freshwater resources provide the main ecosystem goods and services to the people. With the growth in population and socioeconomic development, the demand for water is likely to increase in few years. A sustainable approach to water management is sought to be achieved through an integrated water resources management.

2.2 Ecosystems of the Umba River

The Umba River Basin includes various ecosystems such as mountains, forests, riparian and floodplain vegetation, wetlands, coastal forests, pastures, agricultural areas, aquatic species, terrestrial animals, and human developments. Although the Eastern Arc mountain blocks contain areas of highest biodiversity in the basin, coastal forests and riparian zones also encompass diverse and important ecosystems. The Umba River estuary supports abundant and diverse ecosystems, the majority of which are located at the end of the river, which makes them susceptible to the effects of flow regime changes. Freshwater flow plays important role in maintaining the estuary that provides essential functions and services to the communities living in the area (VAJIKI PFMP 2017).

2.2.1 Estuarine Ecosystem

An estuary is an area freely connected to the sea and having freshwater inflow from rivers. It experiences seasonal variations in physical, chemical and biological parameters, driven by the climate, tides, and river flows. Freshwater and saline water inflows influence the properties of water, habitat structure, channel morphology, nutrient compositions, sediment depositions, and productivity of estuaries. This ever changing environment of fresh and saline water is one of the most productive ecosystems. In spite of their importance, however, they are greatly impacted by excessive abstraction of rivers, pollution, habitat alterations, eutrophication, and overfishing. As a result, the natural functioning of these ecosystems continues to be altered causing significant impact on their productivity and provision of ecosystem services (FIU-GLOWS 2016).

The Umba River estuary is endowed with important terrestrial and aquatic habitats that support rich biological diversity. These include river channel, mangrove forests, sea grass beds, coral reefs, sand dunes and sandy beaches, and other estuarine systems (Mitto et al. 2013; Mocha 2010). The coastal forests comprise unique communities with high drought resilience and adaptation of flora, endemic birds, mammals, and other fauna. They play a significant role in the hydrological cycle by enhancing soil moisture content, mitigating soil erosion, and connecting to other habitats. They provide shelter, nursery, and feeding areas for a large variety of terrestrial and marine biota (MEWNR 2013). These provide essential ecological services, support production, and serves as the source of livelihoods and income-opportunities to the communities.

Characterized by the mixing of freshwater and seawater, the estuary depends on the seasonal variations in freshwater inflows. Rainy and dry seasons in the river basin cause these seasonal fluctuations in the freshwater inflows to which the local ecosystems have adapted. These have strong influence on the distribution and productivity of the coastal and marine ecosystems (Mitto et al. 2013). However a decrease in freshwater inflow to levels lower than the natural seasonal flow regime results in increased seawater intrusion into the estuary. Decreased river inflows can also lead to decreased nutrient and sediment inputs and disrupted lifecycle processes. Hence, maintenance of a balance between freshwater flows and marine inputs is essential for proper functioning of the ecosystems. This should typically follow the natural seasonal flow variation as seen from long-term historical flow data (FIU-GLOWS 2016).

2.2.2 Aquatic Ecosystem

Aquatic ecosystems include areas that are permanently covered by water and surrounding areas that are occasionally covered by water. Environmental regimes influence the composition and structure of aquatic communities and continually modify the suitability of the aquatic habitats. These environmental regimes are affected by temporal variations in streamflow, water temperature, dissolved oxygen concentration, transport of sediment and organic matter, and other environmental conditions (Richter et al. 1998). Streamflow provides adequate habitat for aquatic organisms which enable them to move to feeding and spawning areas and to keep their eggs suspended (Risley et al. 2010).

The aquatic fauna of the Umba River include fishes, prawns, crabs and molluscs (Kwale 2013). The most common families of fish in the area include; Acanthuridae, Carangidae, Coryphaenidae, Gerreidae, Lethrinidae, Lutjaninae, Siganidae, and Sphyraenidae (VAJIKI PFMP 2017). Individual species have specific requirement on the magnitude of discharge, timing of the flow, temperature, and salinity. Hence, longer duration time series of flow data is required to predict the appropriate flow regime and its seasonal variations. The aquatic animals of the Umba River spawn when the floodplain areas are flooded between October and May. Their eggs require sustained flows for approximately 14 to 28 days before hatching. Favourable spawning conditions need to occur once every two years so that they get a chance to spawn in their lifespan.

2.2.3 Mangrove Forests

Mangrove forests occur along the coast in the intertidal area between the land and the ocean. They are among the most productive ecosystems offering a wide range of resources and services including coastal protection, habitat for diverse flora and fauna, nursery and breeding grounds, source of fire wood, and production of timber, poles, boats and other products (Mitto et al. 2013; Bosire et al. 2003). The mangrove forests have also key roles in climate regulation, carbon cycling, flood and erosion control, filtering and trapping of pollutants, retention of nutrients and sediments, and protecting the beaches and adjacent areas from strong winds and sea waves (FIU-GLOWS 2016). Other mangrove services include fishing, recreation, extraction of medicines, cultural uses, grazing, and source of fishing gears. They are resource rich environments which promote a variety of food chains and functions playing vital roles for subsistence and livelihoods of the communities (VAJIKI PFMP 2017). The protection and conservation of these forests is thus important for the continued provision of the ecosystem goods and services.

The mangrove forest of Vanga covers an estimated area of 4,265 ha which is the third largest of the mangrove forests of Kenya. Seven of the ten mangrove species present in Kenya (Wang'ondu et al. 2010) are found in the study area (Table 1). Rhizophora mucronata (Rm) and Ceriops tagal (Ct) are the most dominant species making up about 80% of the total forest cover (VAJIKI PFMP 2017). Freshwater inflows influence the general functioning of the coastal estuary and the seasonal fluctuation of the river flow is adapted by the local estuary. However, when the natural seasonal flow of freshwater is disturbed, the prolonged exposure to seawater elevates stress in mangroves, resulting in increased leaf loss to reduce water loss by transpiration (Wang'ondu et al. 2010; FIU-GLOWS 2016).

Table 1. Mangrove Species Present in the Umba Estuary

S. No.	*Mangrove Species Name*	*Short Name*	*Common Names*	*Salinity Tolerance*
1	Avicennia marina	Am	Mchu	Good salinity tolerance
2	Bruguiera gymnorrhiza	Bg	Muia, Mkifi	Medium salinity tolerance
3	Ceriops tagal	Ct	Mkandaa	Poor salinity tolerance
4	Lumnitzera racemosa	Lr	Kikandaa	Medium salinity tolerance
5	Rhizophora mucronata	Rm	Mkoko, Mrungu, Msisi	Good salinity tolerance
6	Sonneratia alba	Sa	Mpia, Mlilana	Good salinity tolerance
7	Xylocarpus granatum	Xg	Mkomafi, Mronga	Poor salinity tolerance

Sources: VAJIKI PFMP (2017); Mitto et al. (2013)

The phenological events of mangroves depend on the type of species, location and environmental conditions (Okello et al. 2014). However, leaf production is generally higher during the wet season while flowering occurs during the dry months (Wang'ondu et al. 2010). The mangrove plants of the Umba River need water between November and January to germinate. After germination, seedling survival depends on the rate of stage recession of the flow. Mangrove plants then need continuous inundation after their recruitment season. Therefore, the suitable range of freshwater inflows that maintain healthy mangrove plants of the Umba River should follow the natural seasonal flow variation as seen from the long-term historical flow data.

2.2.4 Riparian Vegetation

Riparian vegetation refers to the trees, shrubs, herbaceous plants, and grasses growing on riverbanks and floodplains. They occupy the stream channel between the low and high water marks and the terrestrial landscape above the high-water mark which is influenced by water level fluctuations. Riparian areas provide habitat for many species, serve as pathways for dispersing and migrating organisms, resources for humans, and contribute in the balance of oxygen, nutrients and sediments (Nilsson and Berggren 2000). Riparian vegetation are important for reducing erosion, maintaining stability of river banks, retaining and processing overland runoff, providing habitat and food for in stream fauna, canopy cover that mediates water temperature, and serving other ecosystem services (GLOWS-FIU 2012).

The vegetation along the Umba River is composed of forests, woodland, bushland, grassland, farmland, and swamp vegetation. Some of the common riparian trees include blue gum (Eucalyptus granatum), cashew nuts (Anacardium occidentale), coconut trees (Cocos nucifera), mango trees (Mangifera indica), neem (Azadirachta indica), and whistling pine (Casuarina equisetifolia) (VAJIKI PFMP 2017). Bushes, shrubs, and other plants and trees are present within the riparian zone covering the river banks and floodplains of the Umba River. Streamflow maintains water table levels in floodplain and soil moisture which has strong influence on riparian vegetation establishment and recruitment of seedlings. High river flows, on the other hand, prevent encroachment of riparian vegetation to the main river channel.

The water flow required for the different riparian vegetation species varies depending on their sites and seasons. The riparian plants of the Umba River germinate during the short rainy season, between October and January. The rate of stage recession should be as low as possible to enable the seedling survival of the young plants. After their recruitment season, continuous inundation is required from January to March.

2.2.5 Macroinvertebrates

Macroinvertebrates are organisms that lack backbone and are large enough to be seen without magnification. They live for all, or part, of their lives in water and inhabit different types of freshwater environments, from fast flowing streams to slow moving rivers and wetlands. Their common habitats are rocks, leaves, sediments, vegetation, and other materials present in the stream. Examples of macroinvertebrates include crustaceans, insects, molluscs, and worms. They have important role on nutrient cycles, primary productivity, decomposition, and exchange of materials. Macroinvertebrates are also good biological indicators of water conditions and are commonly used to assess the health of streams. Flood flows shape the physical character of river channel and initiate a return to more natural conditions of a river. These trigger new phase of life cycles (Risley et al. 2010) and encourages communities of macroinvertebrates to rebound to their original biodiversity (Wakitolie 2013; USACE 2017). Therefore, sufficiently high flow, obtained from the natural flow regime, should flow at any time of the year to maintain balance of the species in the Umba river.

2.2.6 Wetlands

Kenya's National Wetland Standing Committee defined wetlands as "areas of land that are permanently, seasonally or occasionally waterlogged with fresh, saline, brackish or marine waters at a depth not exceeding six metres, including both natural and man-made areas that support characteristic biota" (Tiner 2017). Wetlands are generally classified into three main types: inland wetlands including permanent and seasonal rivers, inland deltas and floodplains, lakes, ponds, and marshes; marine or coastal wetlands such as open coast, coral reefs, estuaries, deltas, mangrove forests, and lagoons; and artificial or man-made wetlands (Mocha 2010). Wetlands are also classified as marsh, swamp, and bog based on general and nontechnical descriptions (Tiner 2017). Six classes of wetlands: marine, estuarine, lacustrine, palustrine, riverine, and human made wetlands are present in Kenya (Mocha 2010).

Wetlands play a fundamental role in maintaining climatic and hydrological stability and supporting huge biodiversity. They are important for downstream flood mitigation, groundwater recharge, retention of sediments and nutrients, and water quality improvement. Natural wetlands also provide life-supporting services by moderating local climate and providing habitat for many aquatic and non-aquatic species (Abell et al. 2002; Mocha 2010). Many factors affect the availability of water for wetland formation including climate, topography, geology, soils, vegetation, and human activities. On the other hand wetlands can be significantly impacted by water diversions, construction works, forestry practices, agricultural activities, drainage projects, and other human activities (Tiner 2017).

Every structural and functional characteristic of wetlands are influenced by hydrological regime. The physical, chemical, and biological functions which give wetlands their unique character and habitat value are driven by water availability. Water exchange between rivers and wetland areas plays a key role for maintaining the health of wetlands. The water regime determined by frequency, duration, depth and season of flooding influences the structure and floristic composition of vegetation communities in wetlands. Changes in water level, flooding, and low flows have beneficial effects on the health and productivity of wetlands (Wakitolie 2013; USACE 2017). Determining the actual hydrology of wetlands require long-term monitoring of water levels and water tables (Tiner 2017).

Provision of water flow based on the natural seasonal flow variation as seen from long-term historical flow data can also support the functioning of riverine wetlands. The exchange of water between the Umba River and its floodplain wetlands occur during high flow periods, between September and April. Active exchange of freshwater every 2 years, in this period, can provide healthy conditions to the wetland areas.

2.3 Ecosystem Functions Model (EFM)

The Ecosystem Functions Model (EFM), developed by the Hydrologic Engineering Center (HEC), is designed for analysing the ecosystem responses to changes in flow regimes of rivers and their connected wetlands (USACE 2017). EFM computes statistics that characterize different ecosystem dynamics based on the hydrologic time series (flow regimes) and life history requirements of species (Julian et al. 2015). Flow regimes are composed of time series of daily mean flow and daily mean stage data that reflect conditions at various locations in the study area. Relationships provide statistical representations that link elements of the ecosystem to the characteristics of the flow regimes through statistical and geographical queries. They offer time series controls that allow users to specify a water year range or an individual water year to be computed (USACE 2017; Hickey, Huff, and Dunn 2015).

Seasonal results of EFM are the most direct measure of how ecosystem aspects perform in individual water years and as a progression through time. These results allow habitat suitability to be considered in each water year and correlations to be performed spatially or in terms of habitat areas. Statistical results are pairs of flow and stage data that meet the statistical criteria specified in the relationships. They offer a way to quickly compare alternatives and identify the most effective at achieving project objectives. These results are most useful when many ecological aspects and management alternatives are being considered (Hickey, Huff, and Dunn 2015).

HEC-EFM is applicable to a wide range of riverine and wetland ecosystems, water management concerns, and restoration projects. It helps to define existing ecologic conditions, identify promising restoration sites, assess ecosystem responses, and compare management alternatives according to predicted ecosystem changes. The seasonal and statistical analyses performed by HEC-EFM can be used in actual flow events and in forecast mode to customize hydrographs to produce specific ecological responses (USACE 2017; Hickey, Huff, and Dunn 2015).

2.4 Analysis of Relationships between Flow Regime and Riverine Ecosystems

This study involved statistical analysis of relationships between the historical flow regime and different ecosystem groups of the Umba River. At the beginning of the analysis, priority environmental flow objectives were determined. These involved identifying the river assets, values, and functions that are to be protected and restored in the river. A natural flow regime composed of daily time series of water levels (stages) and discharges was utilized. Analysing the streamflow record involved checking data record consistency and selection of record out of the available data. During the ecological analysis, the functional relationships of the river hydrology and the riverine ecosystem were identified. These include investigation on biodiversity of the river and development of eco-hydro relationships. These require understanding the way in which flows dynamically change in the river by examining the aspects of flow in magnitude, duration, seasonality, and variability.

To obtain the best possible level of eco-hydrological information and understanding, an extensive literature review on hydrology and ecology of the study area was conducted. Study sites for assessing the relationship between habitat availability and water discharge were identified. During the field investigation surveys, data regarding the nature of the river, channel shape and pattern, riparian cover, mangrove plants, wetland areas, and other information on the river were gathered. Relationships and life history information were obtained from published references and study reports prepared by Kenya Marine and Fisheries Research Institute (KMFRI), Vanga Fisheries Department, and Kenya Forestry Service (KFS). Ecological data of the river were then organised in terms of ecosystem groups as aquatic animals, mangrove plants, riparian vegetation, macroinvertebrates, and floodplain wetlands.

HEC-EFM version 3.0 was used to analyse the flow regime of the river and investigate the ecosystem relationships. A stage-flow rating curve, at 3KG01 gauging station, was used to prepare the daily time series data of the streamflow from the observed stage. The flow characteristics of the Umba River were interpreted using daily flow-duration curve, monthly flow, and annual flow distributions. Peak flows, mean flows, and discharges with specified durations, seasonal periods, exceedance probabilities, and stage recession rates were then identified. The daily time series of flow and stage were stored in HEC-DSS and imported to HEC-EFM. Life history information, interpreted in terms of simple statistical criteria, was used to define statistical queries of relationships. This offered control for managing the flow and stage data to be used for the statistical computations. The relationships associate the characteristics of hydrologic and hydraulic time series (flow and stage) with the elements of the ecosystem through combination of four statistical criteria: season, duration, rate of change, and percent exceedance. The relationships used for aquatic animals of the Umba River are shown in Figure 2. Similar relationships were developed for the other ecosystem groups.

In addition to the statistical queries, relationships were also defined using hypotheses, confidences, and indices. Hypothesis was entered to indicate whether a higher river flow helps, harms, or have a non-linear response for the relationship. Confidences were used for prioritizing the ecosystem relationships. Indices were used to group relationships that have common requirements and to look at the net effect of flow regime changes. After importing the flow regime and developing relationships, statistical computations were performed by HEC-EFM. It analysed the flow and stage time series for the specified criteria and produced flow and stage values for each relationship. The seasonal results for the flow regime and the different relationships were compared using EFM Plotter version 1.1.

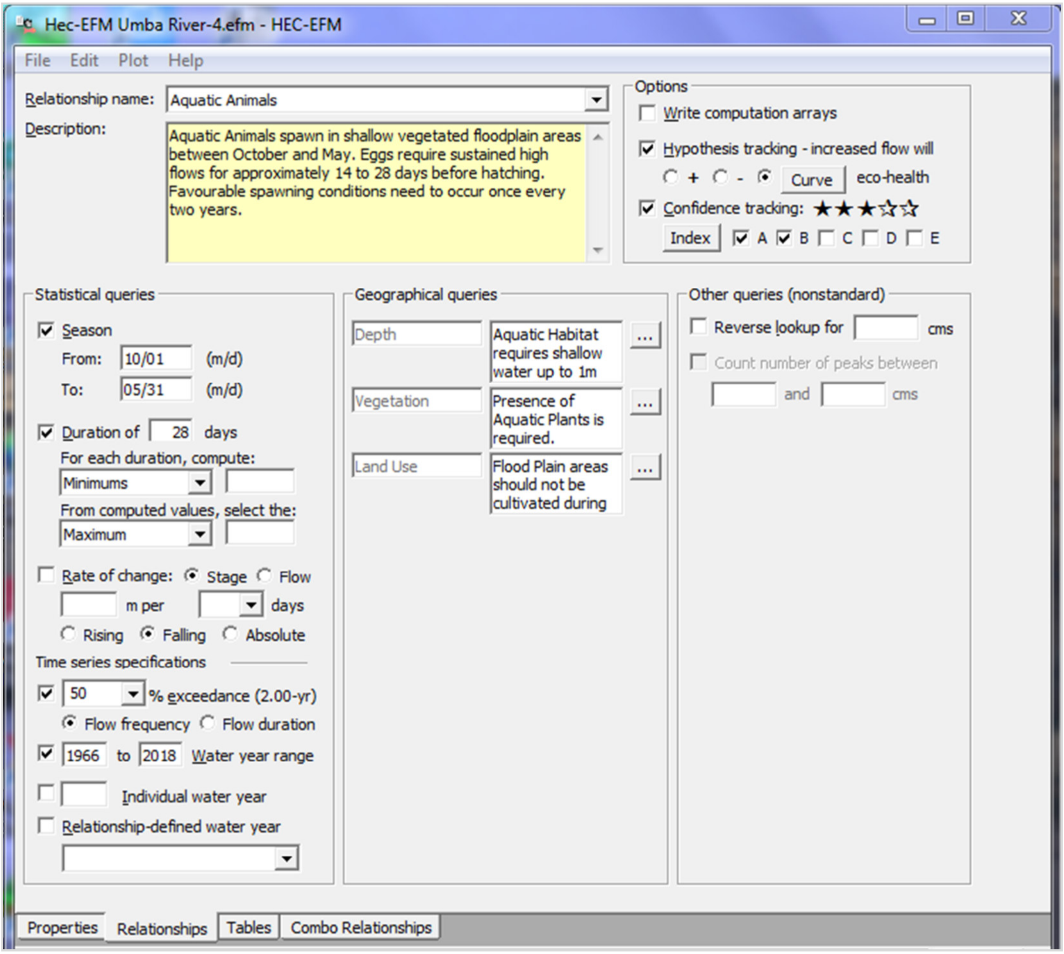

Figure 2. Developing Relationships for Aquatic Animals

3. Results and Discussion

The historical flow data of the Umba River was investigated to understand the seasonal variability in flow that the riverine ecosystem has experienced in the past 50 years. The mean annual flow of the river, for the entire flow period of 1966 to 2017, was found to be 4.41 m^3/s. During this time period, the maximum ever recorded flood was 221.61 m^3/s and the lowest flow was 0.07 m^3/s. The river flow was further analysed to investigate the flow distribution in each month (Figure 3) and to understand the seasonal and inter-annual variability of the flow that the ecosystems have adapted over the time.

The monthly flow pattern indicates a seasonal trend with low flows experienced during the dry periods (June to October and February) and high discharges flowing during the rainy seasons (November to January and March to May). The flow of the river is characterized by high seasonal variability due to the seasonal variations in the climate. The ecosystem in the river and estuary has evolved with this variability of flow over the years.

This is an important aspect to be kept in mind while managing water abstractions and maintaining flow within the river. The graphs of Q-50, Q-80 and Q-95 represent the flow values exceeded by 50%, 80% and 95% of the monthly flows respectively. The annual distribution (Figure 4) of the streamflow shows the historical flow characteristics of the Umba River. The years 1978, 1979, 1997, 1998 and 2015 had higher flows compared to the other years. Most of the remaining years have experienced flows near the overall average of 4.41 m3/s.

A daily flow duration curve (FDC) was prepared by arranging the daily discharge in descending order. The percentage of time that each discharge is equalled or exceeded was then calculated using the Weibull formula (Chow, Maidment, and Mays 1988). The FDC of the Umba River has indicated the flow variability by displaying the complete range of the river discharges from low flows to flood events (Figure 5). The graph shows very steep slopes for the extreme low and high flows indicating that very few flow events were experienced for those flows.

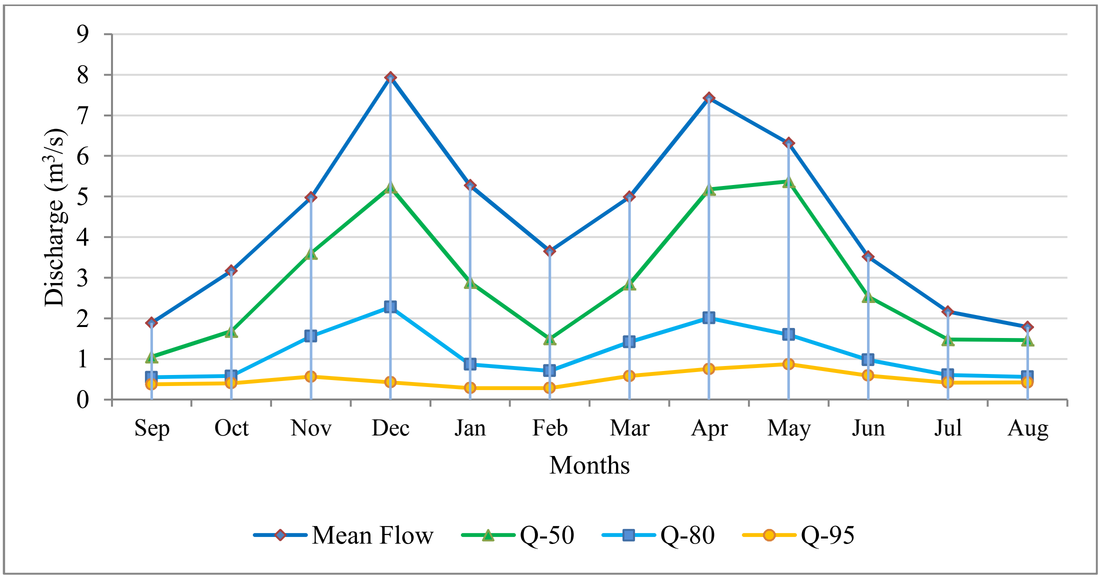

Figure 3. Mean Monthly Flow, 50%, 80% and 95% Exceedance Flows of the Umba River at 3KG01 Gauging Station (1966 - 2017)

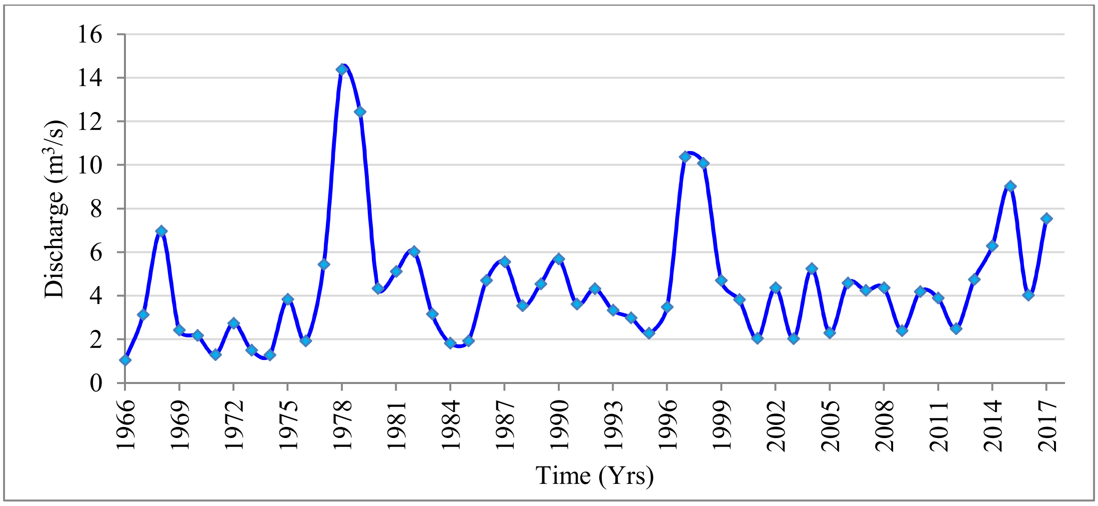

Figure 4. Mean Annual Flow of the Umba River at 3KG01 Gauging Station

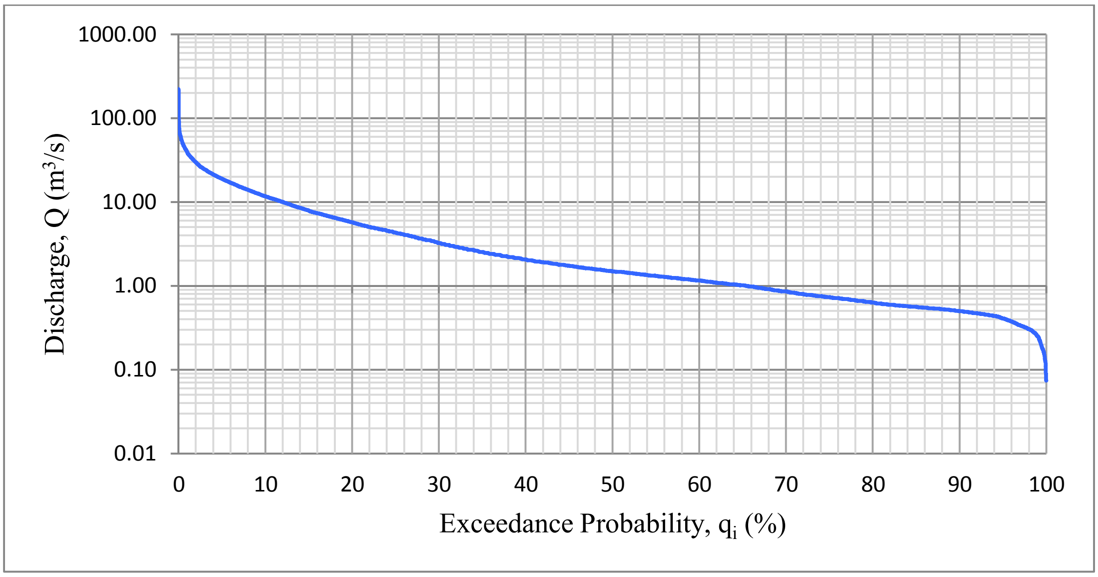

Figure 5. Daily Flow Duration Curve for the Umba River at 3KG01 Gauging Station

A natural flow regime, composed of the daily time series of flow and stage, was utilized in the HEC-EFM model. The ecological links of various communities within the Umba estuary were characterized with the river flow. The eco-hydro relationships were organised into five ecosystem groups: aquatic animals, mangrove plants, riparian vegetation, macroinvertebrates, and floodplain wetlands.

For each ecosystem group, the model extracted the daily river flow data of the specified season from each year to be used for seasonal and statistical analyses. Figure 6 shows the daily water levels (stages) extracted from the selected season of each year for mangrove plants inundation. The left section of the graph shows the selection preferences for the flow regime, relationship (ecosystem group), and the result to be displayed. The right part of the graph presents the time series of the selected water levels in each year of the available natural flow regime.

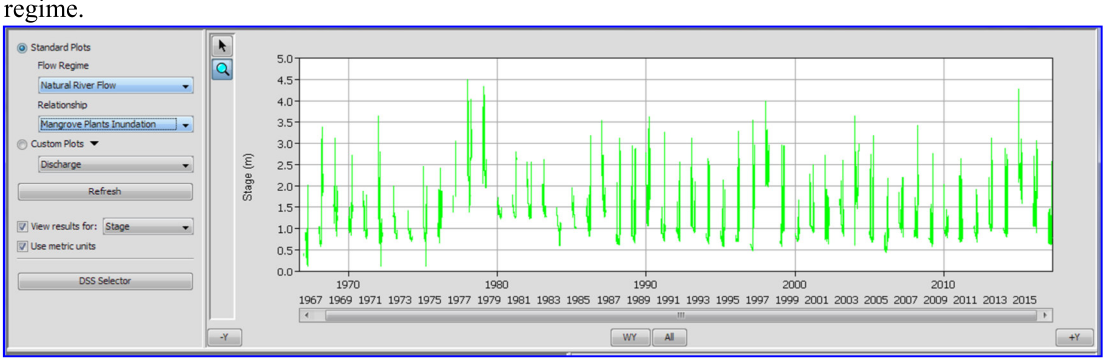

Figure 6. Daily Water Levels extracted from the specified Season of each year for Mangrove Plants Inundation

Seasonal results were computed with the help of HEC-EFM plotter for each relationship to show and compare how the ecosystem groups performed in each year. Figure 7 shows the seasonal results of mangrove plants inundation and the distribution of the ecovalues with their exceedance probabilities. Ecovalues are measures of how well flow regimes meet the needs of relationships and they are computed from the selected flow data based on the hypothesis tracking (USACE 2017; Hickey, Huff, and Dunn 2015). The graph at the lower right section of (Figure 7) shows the distribution of the computed ecovalues plotted against their exceedance probabilities. The performance of the mangrove plants has been found similar for many of the years with the exception of few high performances.

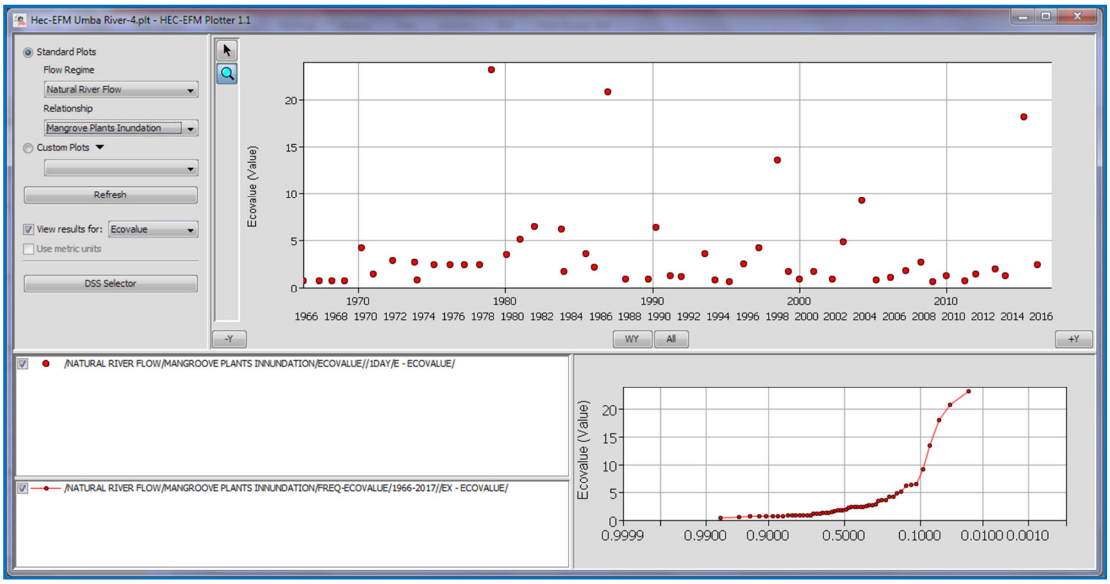

Figure 7. Seasonal Results for Mangrove Plants Inundation and Distribution of Ecovalues with their Exceedance Probabilities

By analysing the historical flow regime in the specified seasons, the statistical results were then computed as stages, flows, and percentage exceedance (Table 2). These are single performance measures that meet the statistical criteria specified for each relationship of the ecosystem groups. From the flow regime, composed of daily time series of water levels (stages) and discharges, the valid years with no missing records in the specified seasons were selected by the model. For the Aquatic animals, a river flow of 3 m^3/s with a water level of 1.3 m, at the gauging station, is calculated from the 41 selected flow years to satisfy the spawning of the aquatic animals in the months of October to May.

Table 2. Summary of the Statistical Results from HEC-EFM

S. N.	*Ecosystem Group*	*Season*	*Valid years*	*Stage (m)*	*Flow (m^3/s)*	*Daily exceedance probability (%)*
1	Aquatic Animals	Oct - May	41	1.3	3.0	31
2	Mangrove Plants Recruitment	Nov - Jan	44	1.7	6.6	18
3	Mangrove Plants Inundation	Jan - Mar	47	1.5	4.6	24
4	Riparian Trees Recruitment	Oct - Dec	45	1.6	5.5	21
5	Riparian Trees Inundation	Jan - Mar	47	1.6	5.5	21
6	Macroinvertebrates	Sep - Aug	41	3.3	48.3	1
7	Floodplain Wetlands	Sep - Apr	50	1.1	1.9	42

To provide the recruitment (November to January) and inundation (January to March) of mangrove plants, the respective flows of more than 6.6 m^3/s and 4.6 m^3/s should flow. Similarly discharges higher than 5.5 m^3/s, flowing from October up to March, can satisfy the recruitment and inundation of the riparian trees. To initiate the natural conditions of the river and encourage the macroinvertebrates, the river needs a flood flow with stage more than 3.3 m at any time of a year. A river flow of 1.9 m^3/s between September and April can support successful exchange of water between the river and the wetlands and help to maintain wetland health. The last column of Table 2 presents the percentage of the daily exceedance probability for the stage and flow values compared with the historical flow regime of the river.

The study focused on evaluating the performance of the existing ecologic conditions including aquatic, riparian, wetland, and estuarine ecosystems. The current state of the Umba riverine ecosystems has been characterized with reference to their connection with the river flow. The statistical relationships between the historical natural flow regime and different ecosystem groups of the Umba River were evaluated using HEC-EFM model. The above results are helpful for identifying the important flow dynamics that satisfy the timing of species life stages and requisite conditions for their success. The findings can be considered as baseline information and when developments are planned in the future, they will offer a way to quickly compare the management alternatives and identify the most effective project that maintains the riverine ecosystems.

4. Conclusions

The study involved statistical analyses of relationships between the flow regime and the riverine ecosystems of the Umba River using HEC-EFM model. The eco-hydro relationships were organised into five ecosystem groups: aquatic animals, mangrove plants, riparian vegetation, macroinvertebrates, and floodplain wetlands. Both seasonal and statistical results are computed based on the flow regime and eco-hydro relationships. The seasonal results presented the performance of the ecosystem groups in each water year of the flow period. The statistical results are computed as stages, flows, and percent exceedance for each relationship. The findings of this study can be considered as baseline information for comparing project alternatives that best meet developmental needs for water without significantly compromising environmental quality of the Umba River. These results can be applied in hydraulic models and GIS to perform spatial analysis. The study is expected to provide input to the management of water resources and assessment of environmental flows. These can be used for providing adequate freshwater flows to maintain the estuarine ecosystem and the services they provide. Additional research is needed to increase the scientific understanding of the biodiversity at species level.

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